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Present and Future Development of Radio Telescopes

BY

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PRESENT AND FUTURE DEVELOPMENT OF RADIO TELESCOPES

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FOREWORD

This report is based upon material presented in a lecture on radio telescopes to the Chicago Section of the IRE in which the author discussed some of the outstanding antenna designs that radio astronomers have developed and are proposing. The antenna requirements in radio astronomy are reviewed and the use of various reflectors, interferometers, and arrays to satisfy these requirements is explained. An appraisal of future developments in the design of radio telescopes is offered.

Revision includes the Arecibo Ionospheric Observatory, the Sac-Fed Hemisphere and the Benelux Cross Antenna; as well as updated information in the other sections.

CONTENTS

ILLUSTRATIONS

SECTION 1
INTRODUCTION

1.1 OBJECTIVE

The objective of this report is to discuss some of the outstanding antenna designs that radio astronomers have developed and are proposing.

1.2 SCOPE

We will begin first by establishing what requirements radio astronomical research imposes upon antenna design. After defining these ground rules, we will discuss and illustrate a few of the ingenious, and sometimes bold, antenna techniques that radio astronomers have either invented or adapted to their needs. We will conclude with an appraisal of the antenna forms that may be developed in the future.

SECTION 2
REQUIREMENTS OF RADIO ASTRONOMY

2.1 ASTRONOMICAL PARAMETERS

In radio astronomy, antennas are used to detect and observe extra-terrestrial sources or, more generally, celestial sources. The parameters of concern during these observations include the position of the radio source, the absolute brightness or intensity over its surface, and its amplitude-frequency spectrum.

The accurate measurement of these astronomical parameters requires (1) a narrow- or high-resolution antenna beam to distinguish one source from another and to pin-point the position of the source, (2) a sensitive antenna, i. e., one with a high ratio of antenna gain to input noise, to measure confidently the brightness of the source, (3) low side lobes to minimize confusion between a weak source in the main beam and a strong source in the side lobes, and (4) accurate calibration of the antenna system, notably beam position, pattern shape, power gain, polarization, and background noise. It is desirable also to have broadband response to enable observation of sources at several frequencies and definition of their frequency spectra, and a steerable antenna beam to track a source across the sky and thereby maximize the time of observation.

A final practical requirement is economy. By economy, we mean an initial investment that one can afford, low maintenance costs and high reliability, potential for growth into a larger structure, and flexibility as a research instrument.

2.2 ANTENNA PARAMETERS

Both resolution and sensitivity require an effectively large aperture. However, we can design an antenna with a moderate aperture area that has a fine beamwidth. Interferometers, synthetic apertures, and other signal processing antennas fall into this category. We will have more to say about this later.

The sensitivity of a radio telescope can be spoiled by lack of discrimination due to high side lobes pointing at hot sources or moderate lobes distributed over an extended warm source. Techniques for side-lobe cancellation have been used extensively by radio astronomers.

Many of these methods, however, are narrow-band and therefore limit the useful bandwidth of the antenna system. On the other hand, broadside arrays with broadband elements and reflectors with broadband feeds can extend the useful bandwidth of a radio telescope.

The antennas which radio astronomers have designed and operated and are proposing today are varied and numerous (Ref. 1). In this report we shall analyze only a few current and particularly significant developments.

SECTION 3
ANTENNA TECHNIQUES

3.1 SINGLE APERTURES

Having made these introductory remarks, we will now turn first to single-aperture structures, i.e., fixed and steerable reflectors, often referred to as "wide-aperture antennas."

3.1.1 Lincoln Laboratory 120-Foot Paraboloid

Paraboloids are classical examples of collecting apertures that can provide broadband, sensitive, narrow-beam operation. The large number of "dishes" that are used in radio astronomical research at VHF-UHF and microwave frequencies illustrates their desirability.

A recent example which is shown in Figure 1 is the Lincoln Laboratory 120-foot paraboloid being constructed at Haystack Hill in Massachusetts for radar astronomy experiments (Ref. 2). This 120-foot az-el dish is fed Cassagrainian style by a horn at the vertex that illuminates a 9-1/2-foot secondary reflector (hyperboloid). This arrangement will achieve a low antenna temperature compatible with a maser receiver and will produce a high gain-to-noise ratio (Refs. 3, 4). A 150-foot, metal space-frame radome protects the antenna structure from wind loads and, to a large extent, from differential thermal expansion caused by the sun. The expected beamwidth at the nominal operating frequency of 8000 Mc/s is 4.2' of arc.

3.1.2 C.S.I.R.O. 210-Foot Steerable Paraboloid

A recently completed "big dish" is the one shown in Figure 2, a 210-foot, alt-az paraboloid (Ref. 5) located in wheat country 200 miles west of Sydney, Australia. It has been designed to detect 21-cm radiation emitted by atoms of neutral hydrogen in the galaxies. In this regard, because of higher surface accuracy and closer mesh, this antenna will perform better than the well-known 250-foot one

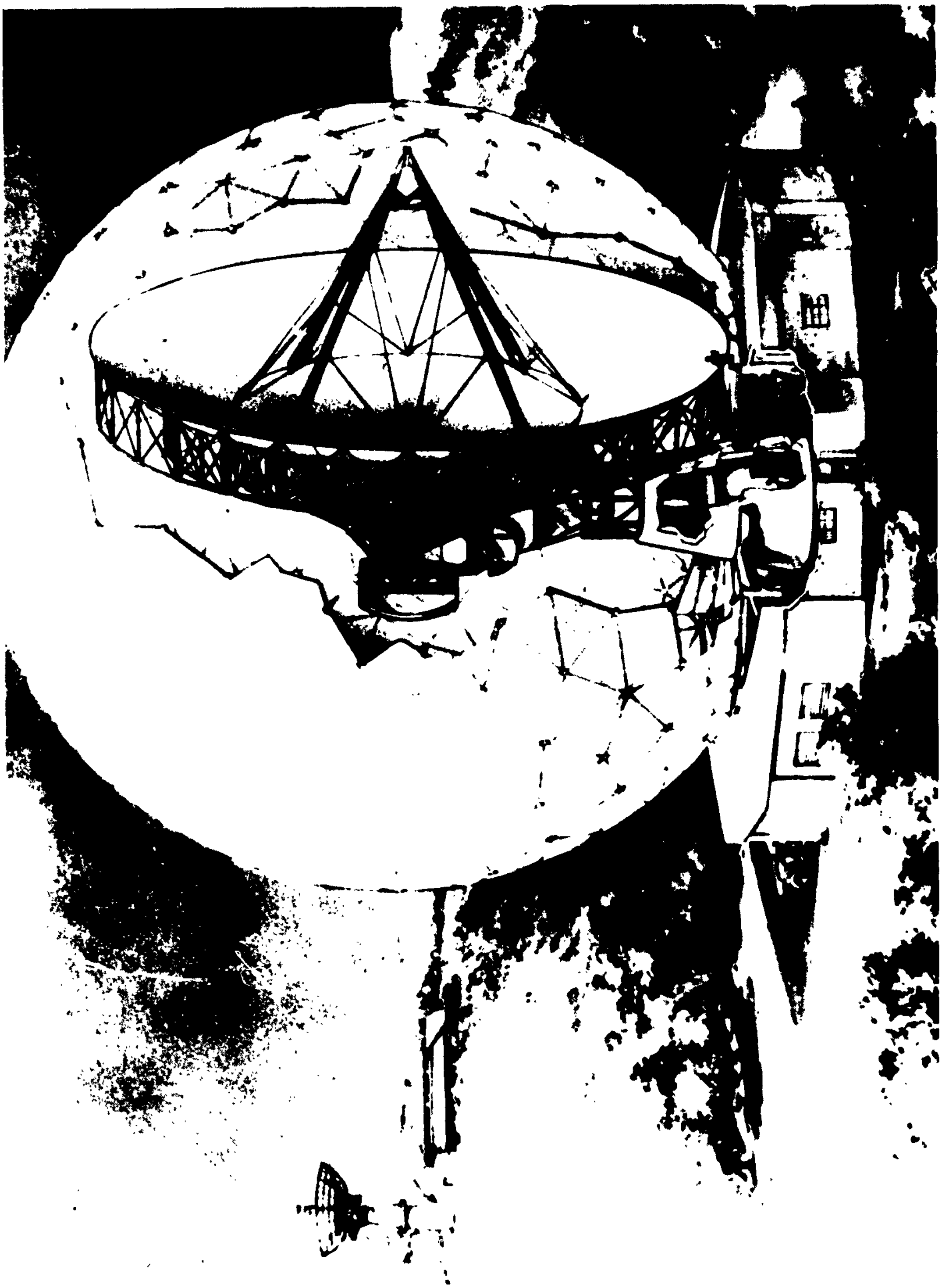


Figure 1 Lincoln Laboratory 120-foot Paraboloid

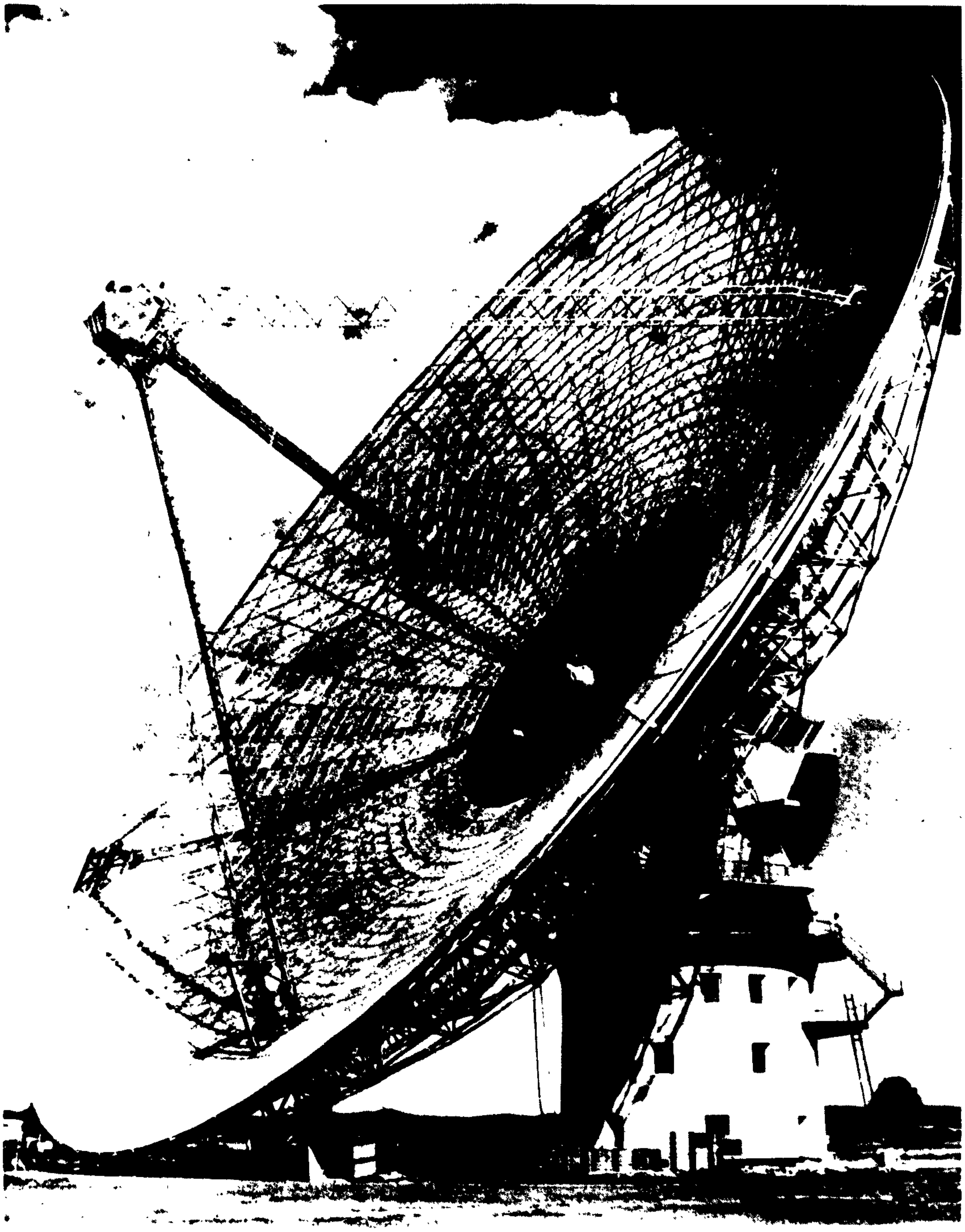


Figure 2 Australian 210-foot Steerable Paraboloid

at Jodrell Bank, England, which was designed before the discovery of hydrogen-line radiation in 1951. The beamwidth of the Australian antenna is 15', and is pointed to within 1' of arc by a unique drive and control system in which any deviation between the polar axis and the antenna axis is sensed optically. The deviation is corrected in altitude and azimuth, thus transforming the drive from equatorial coordinates to alt-az coordinates (Ref. 6).

3.1.3 Limitations on Aperture Size

Large aperture areas such as those discussed above are required in some radio astronomical work to provide sensitivity along with resolution. It seems (Refs. 7, 8), however, that because of structural deformations and limitations in surface accuracy which can be manufactured with present techniques, the maximum allowable physical area of a paraboloidal reflector is about $\lambda^2 \times 10^6$. The corresponding minimum achievable resolution is about 3.5', while radio astronomers are now looking for beams no greater than 1' of arc wide.

The cost of steerable paraboloids is illustrated in Figure 3 by a cubic polynomial best-fit to the reported cost of a number of operational and developmental paraboloids between 60 and 300 feet (Refs. 9 to 13). The curve does not differentiate among reflectors with different mounting structures and other electro-mechanical specifications, such as nominal or maximum frequencies, rms surface contours and environmental conditions. For comparison, a cubic curve was fit through points characterizing antennas operated nominally at 1420 Mc (see Figure 3). In order to break these limits of cost, gain, and resolution, new principles have been applied by antenna designers and radio astronomers to develop economical alternatives to large, steerable paraboloids. One of these techniques consists of subdividing the reflector surface into individually adjustable, highly accurate segments. The Soviet 72-foot paraboloid operated at 8 mm to generate a reported beam of 1.9' is a prime example of this technique (Ref. 14). Another method is to immobilize the reflector in a fixed position above ground and move something smaller such as a lighter structure (e.g., a feed or secondary reflector). A third mechanism is to support the reflector surface on the ground.

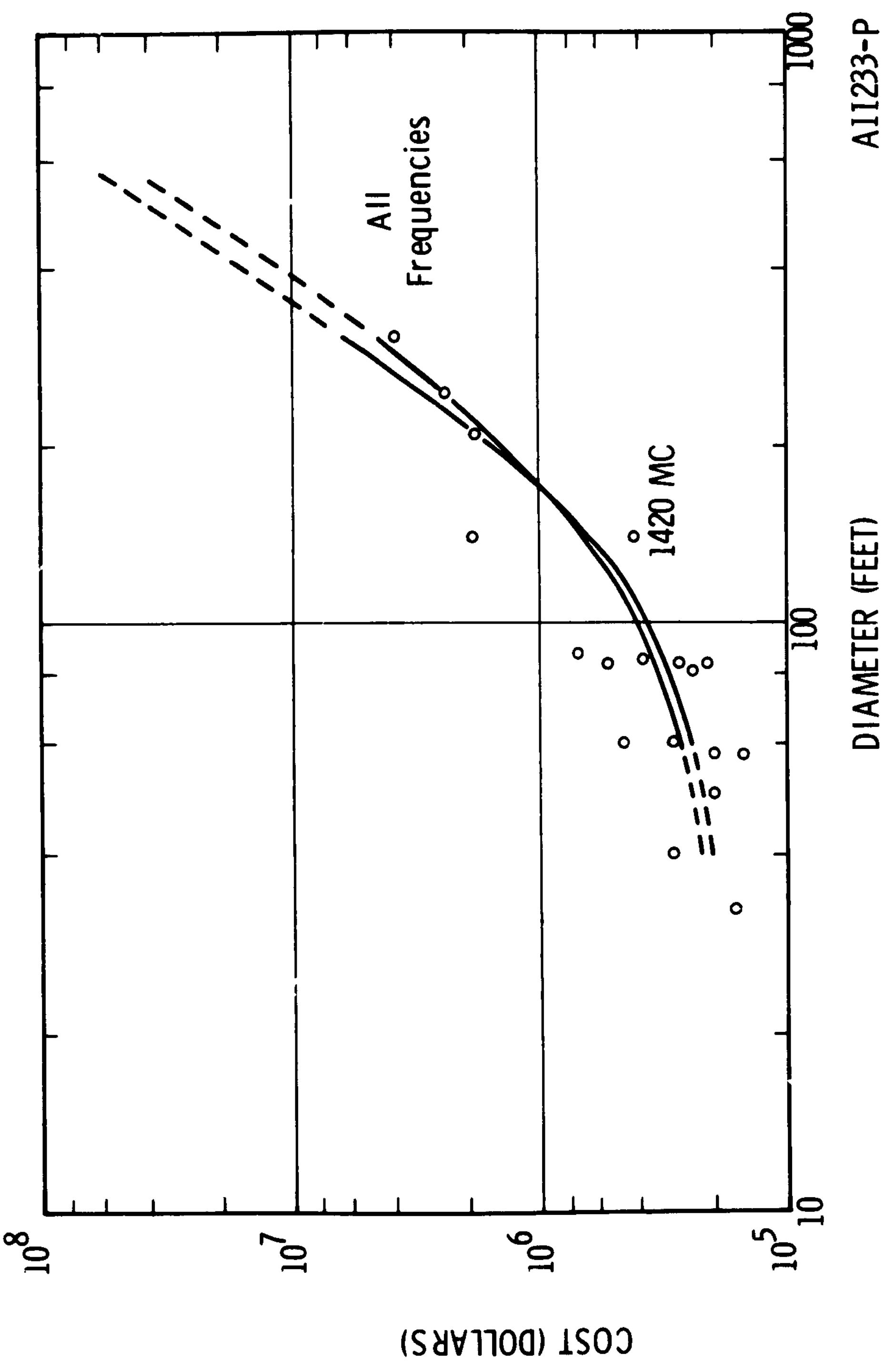


Figure 3 Cost of Steerable Reflectors

3.1.4 Philco WDL 450-Foot Spherical Reflector

The antenna structure proposed recently by Philco WDL (see Figure 4) consists of a fixed 450-foot-diameter spherical bowl, a movable line feed to correct for spherical aberration, and a standing spherical section, 280 feet high and 390 feet wide at the base (Ref. 15). The standing spherical section can be rotated on railroad tracks along the periphery of the bowl to provide 360^{o} coverage in azimuth and horizon-to-horizon coverage in elevation. From model studies at Ku-band the beamwidth at 2300 Mc/s is expected to be less than 6'.

We recall that, contrary to a parabolic surface, parallel rays incident upon a spherical surface cross the axis at different points. This is called "spherical aberration," and is shown in Figure 5. A line feed distributed along the axis which intercepts the rays as they cross will collect the dispersed energy (see Figure 5b). This approach has been adopted for the 1000-foot spherical bowl at Arecibo, Puerto Rico (Ref. 16). A model of this large reflector is on display at the Air Force Cambridge Research Laboratories and is shown in Figure 6 (Ref. 17). Alternatively, as shown in Figure 5a, a sac feed will focus the rays to a point where a secondary feedhorn collects the energy (Refs. 18, 19). The portion of the hemisphere illuminated by each of the feeds is about the same, but the sac has a greater operating bandwidth and is simpler to scan (Ref. 20).

Currently under study is a sac-fed hemisphere that can be fixed in the ground or that can be supported above ground, as shown in the conceptual drawing in Figure 7.

3.1.5 Ohio State 360-Foot Standing Parabola

Ohio State University's contribution to an economical, wide-band, narrow-beam antenna structure (Ref. 21) is shown in Figure 8. A tiltable, flat reflector, 260 feet long by 100 feet wide, reflects energy from the sky into a standing parabolic section, 360 feet long by 70 feet high, which in turn focuses the reflected energy into a feedhorn above a horizontal ground plane. The ground plane is concrete overlaid with metallic paint. The photograph in Figure 8

Figure 4 Philco WDL 450-foot Spherical Reflector (Model)

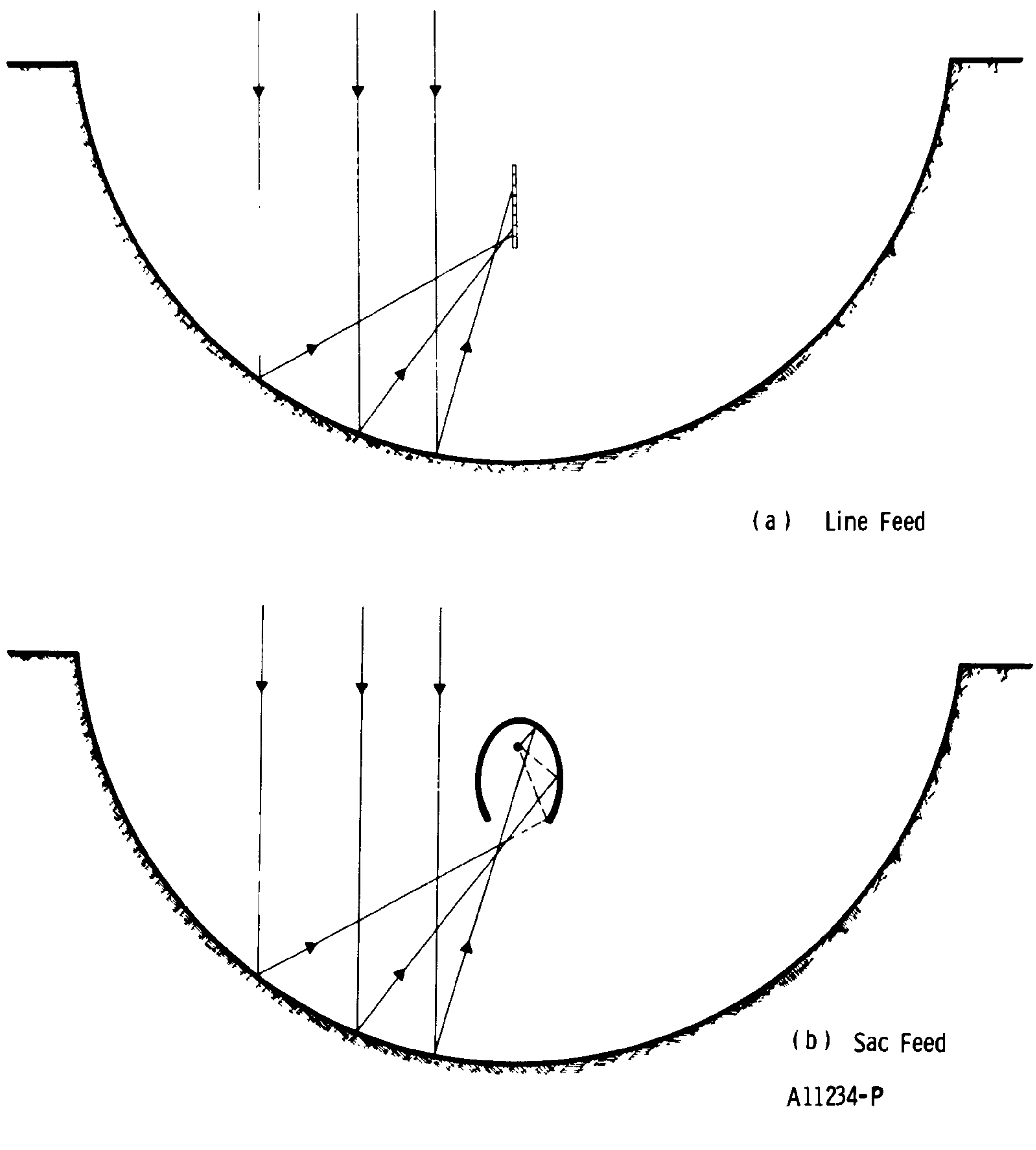
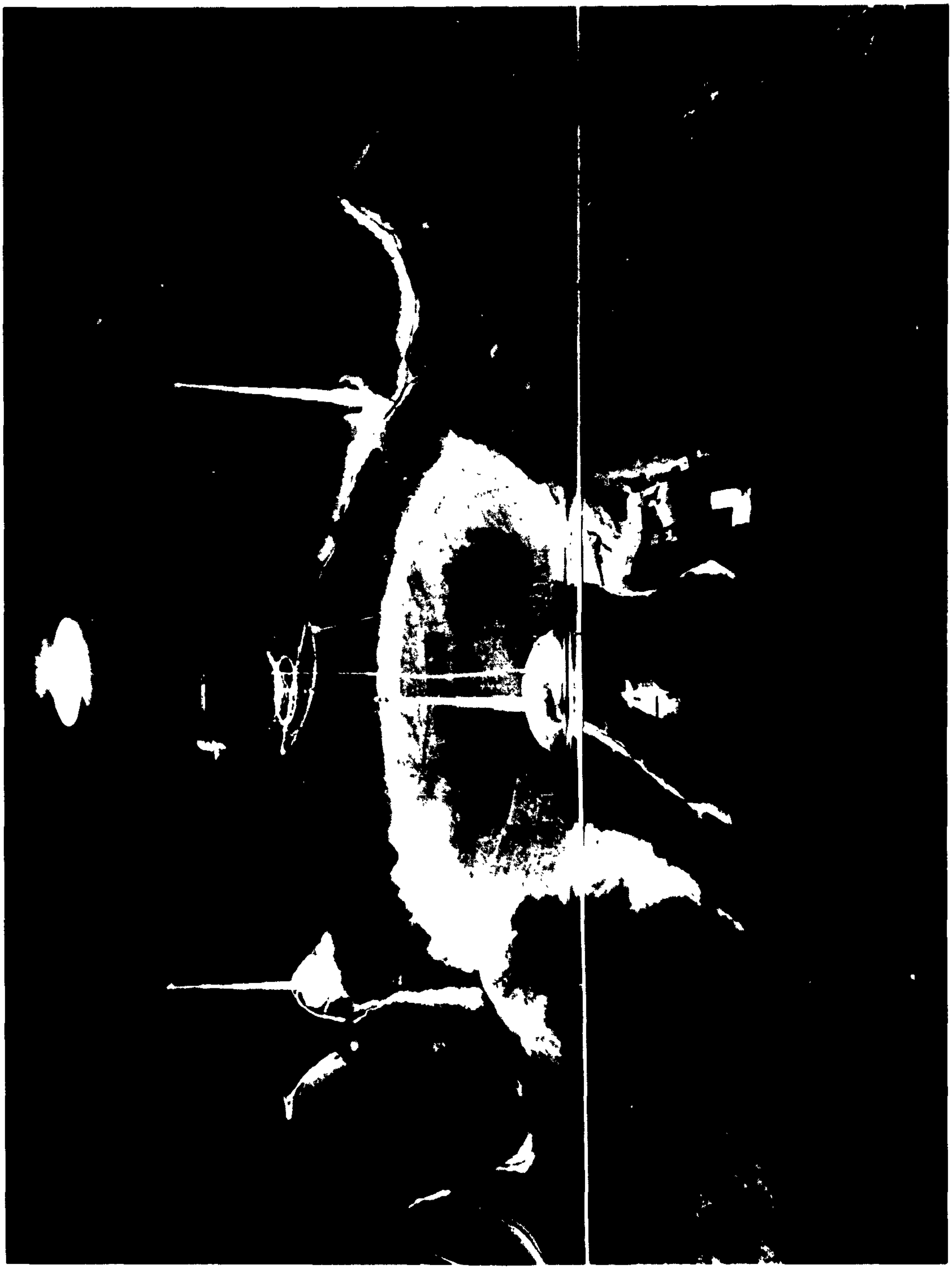


Figure 5 Spherical Aberration Correctors



1000 Foot Spherical Reflector

Figure 7 Sac-Fed Hemisphere

Figure 8 Ohio State University 360-foot Standing Parabola

does not show the horn clearly; however, the sketch in Figure 9 illustrates the geometry well. The expected beamwidths at 250 Mc/s are about 1° in right ascension and 3° in declination (Ref. 22). The design of this large antenna is one solution to maximizing the ratio of aperture area to dollar cost.

The idea of a standing reflector design has been adopted at the Observatoire de Paris at Nançay, France, where a standing spherical section 1000-feet long by 115 feet high, is illuminated by a horn-fed paraboloid and a flat-plate reflector at frequencies as high as 8500 Mc/s (Ref. 23).

3.1.6 University of Illinois 600-Foot Parabolic Cylinder

Figure 10 illustrates an effective approach by the University of Illinois to a large, low-cost antenna with good surface accuracy and very low side lobes (Ref. 24). It is an earth-supported parabolic cylinder 600 feet long by 400 feet wide, whose focal line lies in the plane of the meridian. A 425-foot long array of 276, non-uniformly spaced, conical spirals lies along the focal line, shown in Figure 11.

The feed of this radio telescope is unique in two ways: (1) the elements of the array are circularly polarized and, therefore, any desired time-phase variation can be achieved by mechanically rotating adjacent elements by some angle ϕ_j (Ref. 25), and (2) to minimize the cross-polarized response of the antenna to randomly polarized radiation from the radio sources under observation, the phase α_j introduced by the transmission line at each element is also randomized by spacing the elements at random.

At 611 Mc/s a pencil beam of about 20' is generated and can be steered $\pm 30^{\circ}$ from the zenith in declination by adjusting the phase of the conical spiral elements (Ref. 26).

3.2 MULTIPLE APERTURES

If greater resolution than we have described so far is needed, much larger apertures are required, and it soon becomes evident that several apertures should be coupled to yield the equivalent of an impractically large, single reflector.

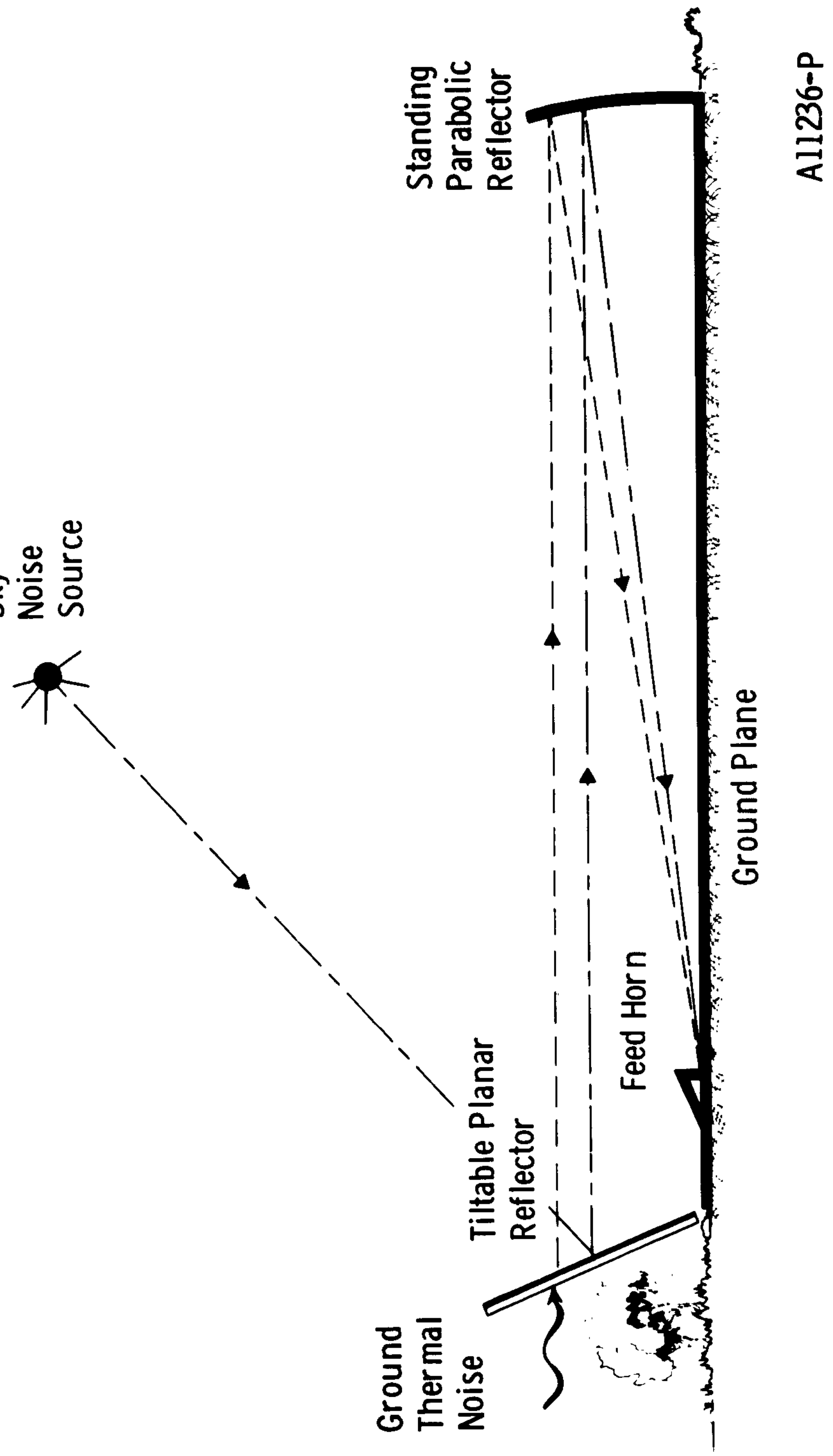


Figure 9 Standing Parabolic Reflector

Figure 10 University of Illinois 600-foot Parabolic Cylinder

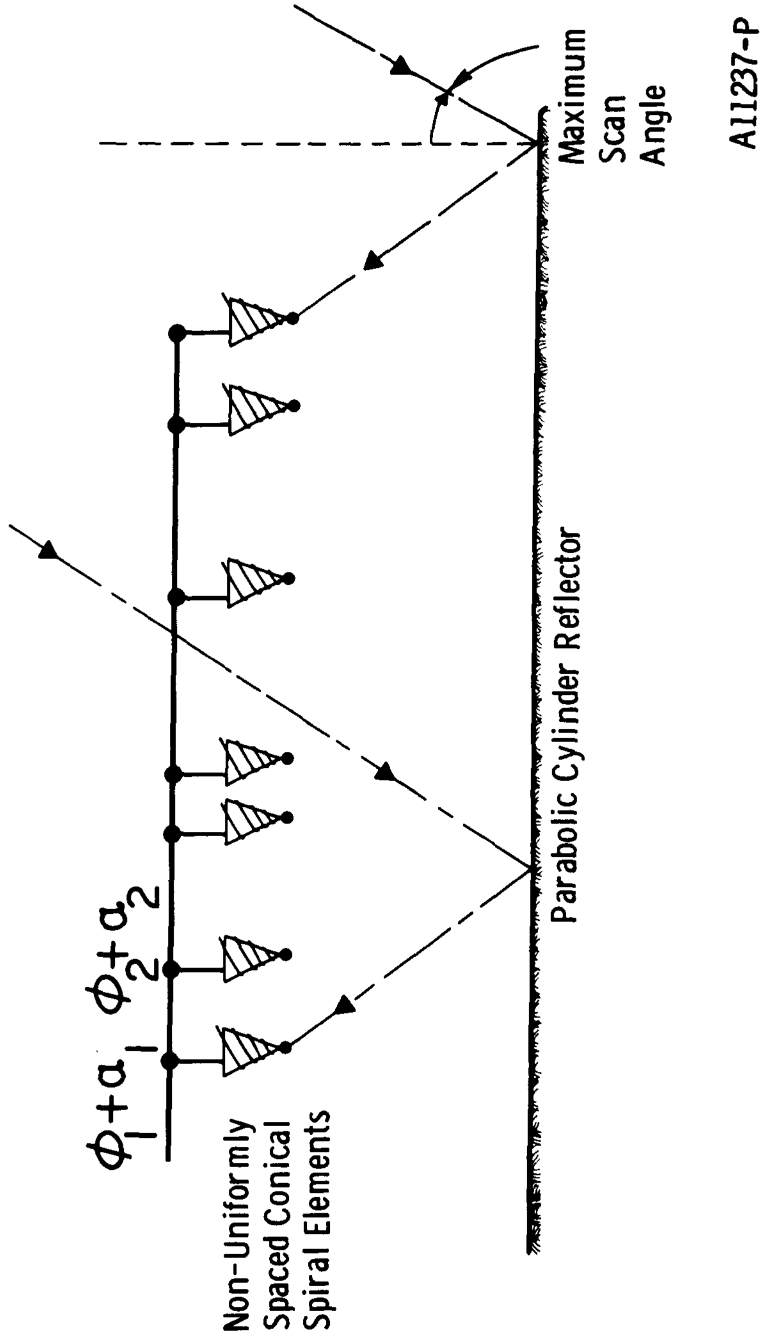


Figure 11 Array-Fed Parabolic Cylinder

The term "equivalent" must be related to particular antenna parameters. Of direct interest are beam resolution, sensitivity or the gain/noise ratio, scanning and tracking ability, and the operating bandwidth. For example, an array of interconnected steerable reflectors will provide resolution, beam scanning, and sensitivity. An array of earth-supported reflectors can provide the same resolution and gain-to-noise ratio but with less scanning ability (unless the WDL-proposed spherical antenna system is used). The operating bandwidth in both cases depends upon the angle of scan from the zenith and the particular arrangement of reflectors.

Although various analyses (Refs. 27, 28) have indicated that a large multiple-aperture antenna is generally less expensive than the equivalent very large, single aperture types, the complexity of feeding systems for these arrays has challenged, although not prevented, our ability to control amplitude and phase. It must also be remembered that the sensitivity of an antenna depends upon its actual collecting area, so that in many multiple-aperture radio telescopes extremely narrow beams have been generated without concomitant sensitivity. Evidently tradeoffs affect the decisions of radio astronomers as well as those of communication engineers.

3.2.1 California Institute of Technology – Two-Element Interferometer

Since progress in radio astronomy depends upon the quality of the observations, radio astronomers have capitalized upon their backgrounds as physicists to adapt or develop new antenna designs.

To increase the resolving power of available apertures beyond that attainable with single-aperture antennas, such as the reflectors just discussed, radio astronomers have adapted the Michelson stellar interferometer to radio waves. The radio analogue looks quite different. For example, Figure 12 shows the two-element interferometer at the Owens Valley Observatory, operated by the California Institute of Technology, which consists of two 90-foot, steel-mesh paraboloids separated by a variable distance up to 1600 feet along railroad tracks in either the north-south or east-west directions (Ref 29). This antenna

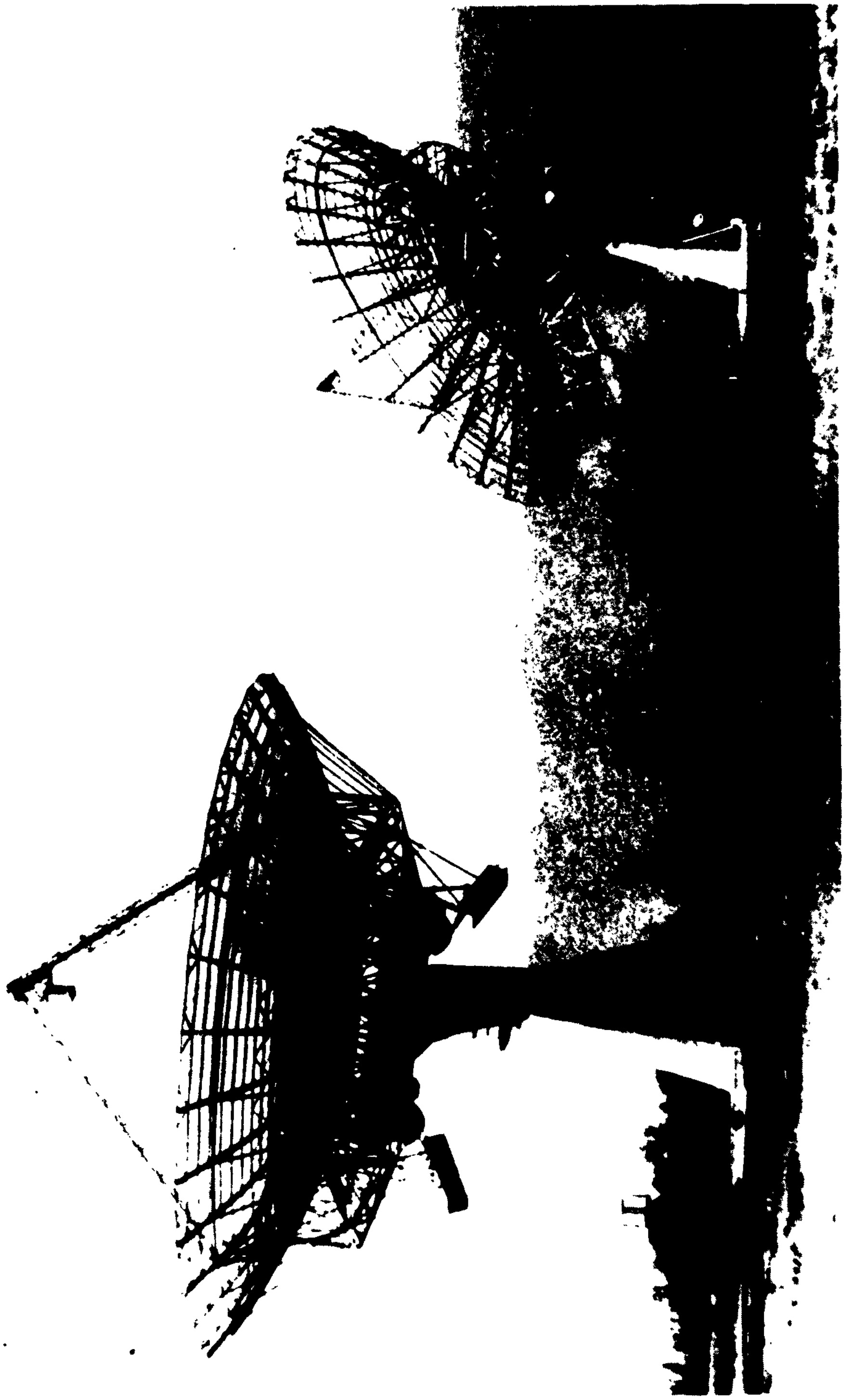


Figure 12 California Institute of Technology Two-Element Interferometer

is used to catalogue the position and extent of discrete sources and to chart the distribution of radio noise in our galaxy at 960/Mc/s with a beamwidth as fine as 2' within a ±6" pointing accuracy (Ref. 30).

The principle of operation of this antenna is illustrated in Figure 13. If a plane wave propagates toward the interferometer at an angle θ with respect to a line normal to the baseline of length L, the radiation reaching the antenna element on the left of the figure travels an extra distance of $L \sin \theta$. A phase difference of $2\pi(L/\lambda) \sin \theta$ then exists between the two elements. Therefore, as the direction of the source of radiation changes (for example, due to rotation of the earth), the signals at each antenna will be alternately in and out of phase. The resulting multi-lobed directional pattern is indicated in polar form on the sketch. The tapering of the interferometer pattern follows the response pattern of the paraboloidal elements and prevents confusion with sources other than the one being observed. Since the separation can be made large and the lobe widths depend reciprocally upon it, very narrow lobes can be achieved. The maximum gain, of course, is no larger than that which can be obtained from the total physical area of the two reflectors.

The operation of the interferometer is based upon pure multiplication and is therefore identical to that of the phase-switching interferometer introduced by Ryle (Ref. 31). Phase-switching or lobe-switching operates as follows: The antennas are connected alternately in phase and out of phase either by introducing and removing a half-wavelength of line at the output of one of the antennas, or by electronically switching the phase at IF. The output consists of an amplifier tuned to the switching frequency and a synchronous or phase-sensitive detector so that the output terminals yield the mean difference between the output of the receiver in the two positions (Ref. 32).

3.2.2 National Research Council 600-Foot Compound Interferometer

At the National Research Council in Ottawa, Canada (Ref. 33) a horn, 150 feet long and fed by a slotted waveguide array, is used as an interferometer with a four-element grating antenna that consists of four cylindrical parabolas, 8 by 10 feet, separated by the length of the horn (see Figure 14).

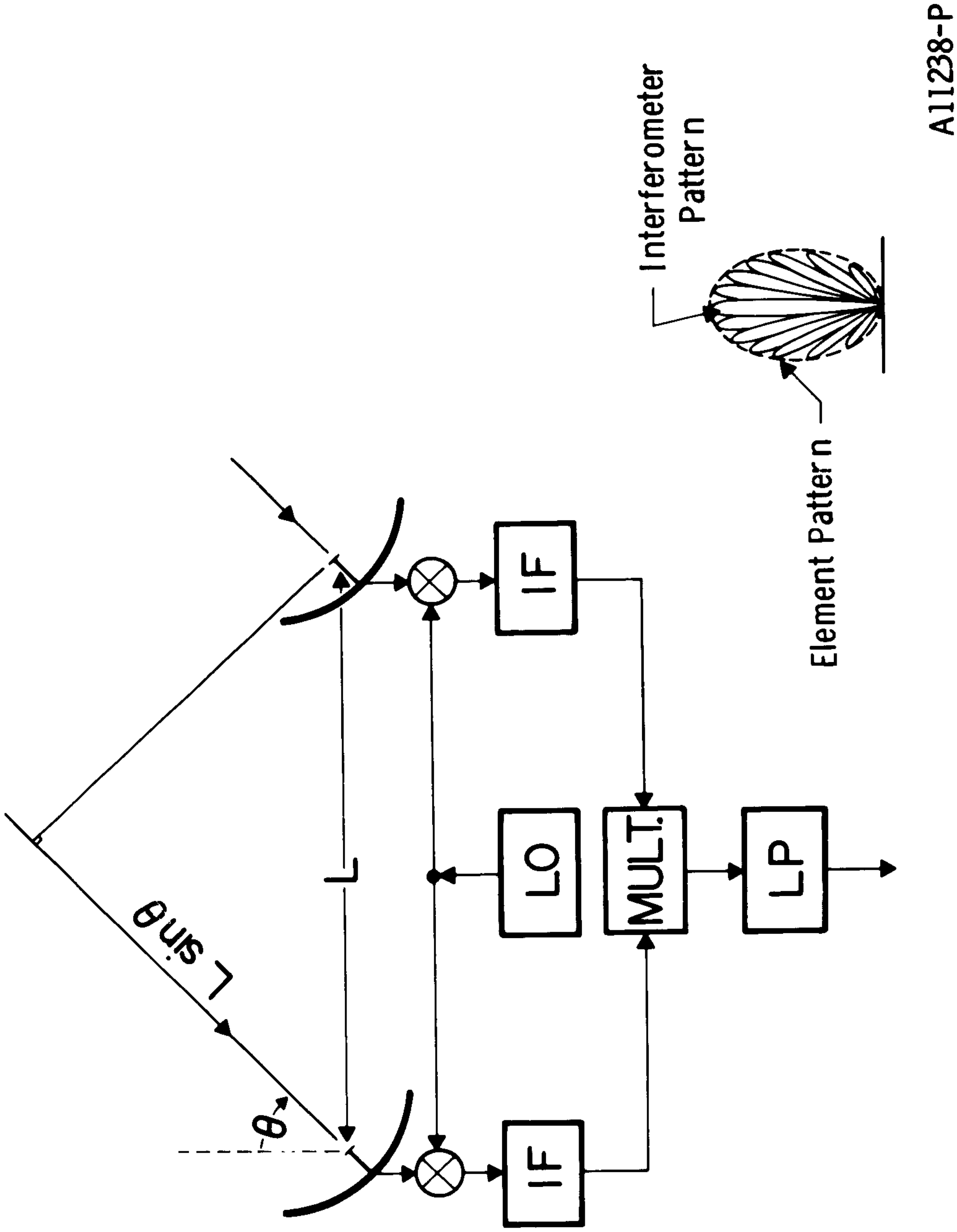


Figure 13 Two-Element Interferometer

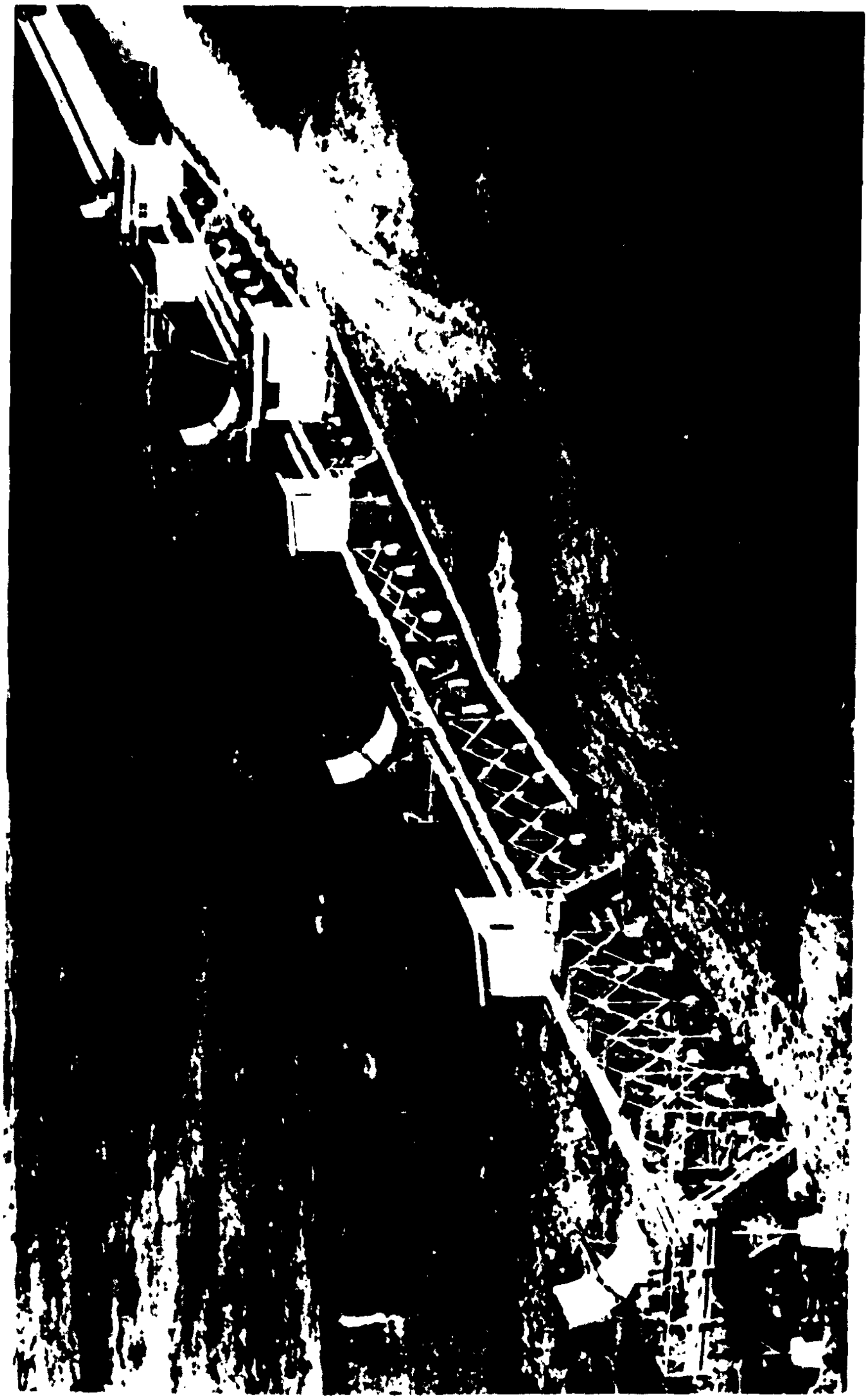


Figure 14 National Research Council (Canada) 600-foot Compound Interferometer

This interferometer, whose overall length is 600 feet, operates between 2800 and 3000 Mc/s as a meridian telescope to examine the surface brightness of the sun with a narrow fan beam of 1.2' in the east-west direction and 2° in the north-south direction.

The sketch in Figure 15 illustrates the principle of operation: the array-fed horn produces a single-lobed, sin x/x pattern where $x = \pi(L/\lambda) \sin \theta$, L/λ being the length of the array in wavelengths, and θ the angle off broadside (Ref. 34). The 4-element grating produces a multiple-lobed, sin 4x/ (4 sin x) pattern whose phase is continuously modulated linearly with time at a rate of 15 cps. The two antenna outputs are multiplied and phase-detected to yield signal power proportional to

$$\frac{\sin 4x}{4x} \cos 4x ,$$

where the cosine term is the "beam-sharpening" array factor based upon a separation between the phase centers of the two elements equal to twice the length of the continuous aperture.

Since this resultant compound interferometer pattern is derived actually from the appropriate sum of single interference patterns that arise from operating each of the grating elements as a phase-sensitive interferometer, the normalized power pattern may be expressed equivalently as (Ref. 35)

$$\frac{\sin x}{x} (\cos x + \cos 3x + \cos 5x + \cos 7x).$$

In general, this form of the reception pattern is

$$\frac{\sin x}{x} \sum_{n=1}^{N} \cos (2n - 1)x = \frac{\sin 2NX}{2NX} ,$$

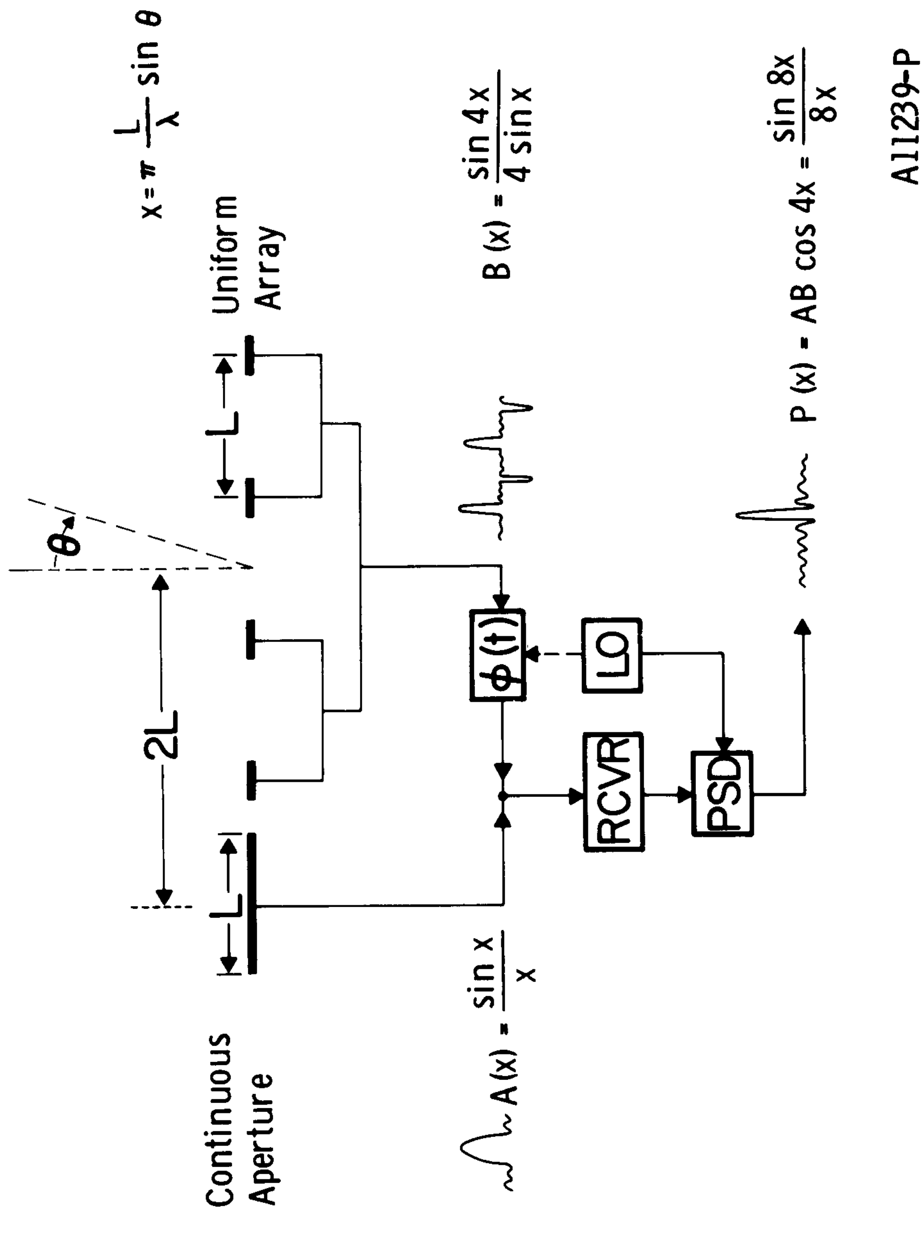


Figure 15 Compound Interferometer

which is a pattern equivalent to that of a continuous aperture of length 2NL, where N is the number of elements multiplied with the continuous array. In our case N = 4. The beamwidth is one-half of what it would be for a uniform aperture of length 4L.

The performance of this antenna consists essentially of selecting one of the grating lobes by the single lobe produced by the horn and a sharpening of this selected lobe by the cosine interference term which develops from a separation of the phase centers of the two antennas.

3.2.3 Stanford 375-Foot Pencil-Beam Interferometer

To measure complex noise distributions, a pencil beam should be generated to resolve the details and to locate special regions of emission. The leading development in this area is the pencil-beam interferometer introduced by Christiansen at Sydney, Australia, in 1953 (Ref. 36). A typical descendant, shown in Figure 16 is Stanford University's cross, each arm of which consists of 16 ten-foot paraboloids arranged along a 375-foot line (Ref. 37). In the frequency range of 2700 to 3350 Mc/s, the cross radio telescope produces multiple beams (or fringes) 3.1' of arc wide that scan the sun in television fashion (Ref. 38).

The pencil-beam interferometer combines the principles of the wide-spaced, multi-element array and of the Mills Cross (Ref. 39). As Figure 17 indicates (see sketch in lower left-hand corner), each array produces a series of very narrow fan beams whose amplitude envelope is determined by the pattern of the individual elements. By mixing the outputs from each array alternately in equal and opposite phase and phase-detecting the modulated signal, a pencil-beam response is produced which is proportional to the product of the individual voltage patterns of each array. The pattern of the interferometer cross consists of a number of widely spaced pencil beams shown at the intersection points on the sketch.

Figure 16 Stanford University 375-foot Pencil-Beam Interferometer

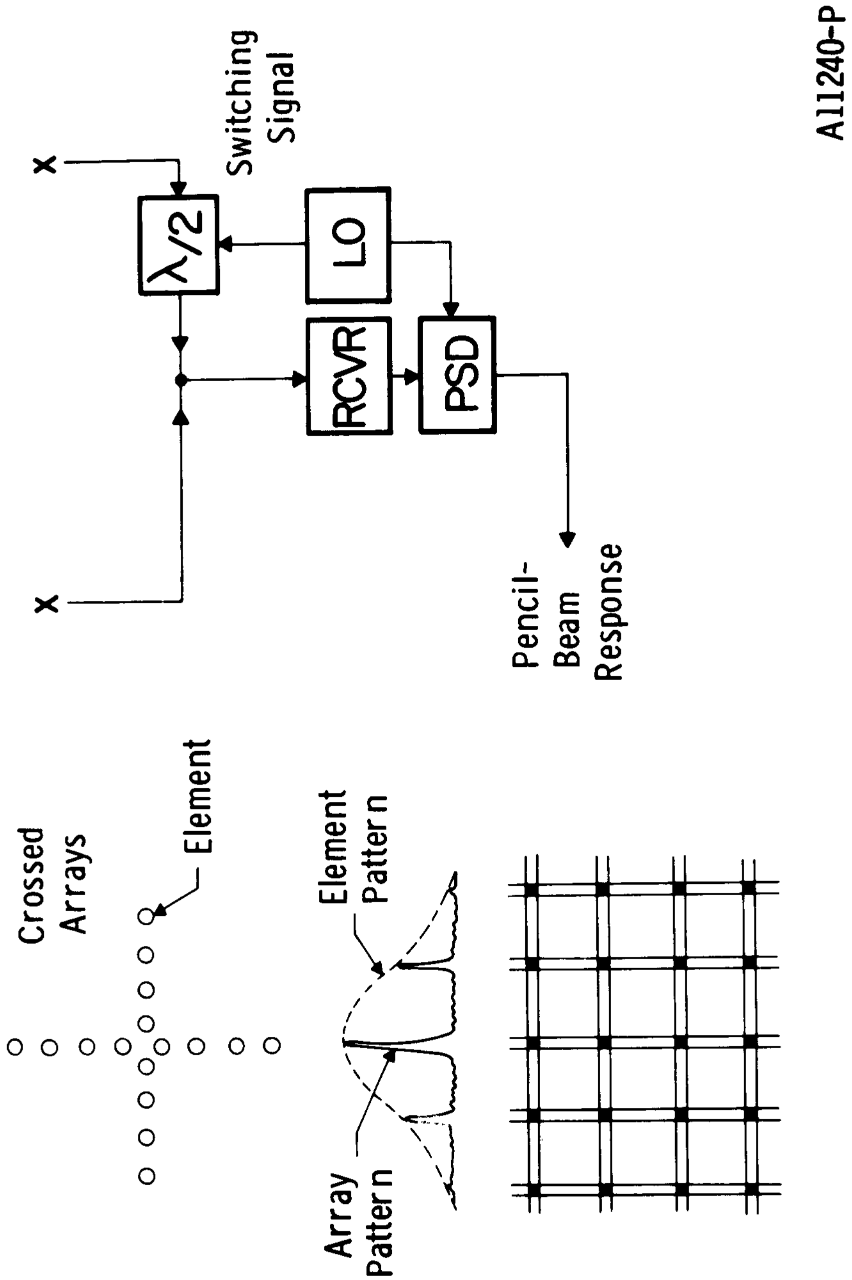


Figure 17 Pencil-Beam Cross-Interferometer

By introducing a linear phase gradient along one of the arms, which is done by varying separate phase shifters at each element (Ref. 40), the location of these pencil beams may be shifted.

3.2.4 Serpukhov 3280-Foot Cross Antenna

If, in addition to resolution, one wishes to increase the sensitivity in a cross antenna, the cross can be constructed of two continuous apertures. An example is the two cylindrical parabolas under construction at the Oka Radio Astronomical Station near Serpukhov, outside Moscow (Ref. 41). Figure 18 shows the 37 60-foot towers supporting a 3280-foot, wire-surfaced, parabolic cylinder 131 feet wide. This is the east-west arm and is rotated about the long axis by simultaneously energized, synchronized motors, one of which is atop each tower. The orthogonal north-south arm under construction is a fixed parabolic cylinder whose fan beam will be steered by means of a line feed consisting of a phased array of dipoles. The antenna will be used to examine the solar corona between 50 and 130 Mc/s, with a beam width of about 15' at 100 Mc/s.

A similar cross has been designed for the University of Bologna in Italy (Ref. 42), except that the north-south arm is an array of parabolic cylinders; while a one-mile cross of two parabolic cylinders is being designed for the University of Sydney in Australia (Ref. 43).

It has been demonstrated (Ref. 44) that, if one removes one-half of an arm to form a T, the gain will decrease, as expected, but the resolution will remain the same. One may look upon this identity between the phase-switched cross and the T in terms of what has been called the "spectral sensitivity function" — essentially the difference between the complex auto-correlation functions of the aperture field distribution when the antennas are connected first in phase and then out of phase (Ref. 45). The T contains all possible spacings and directions between elements that exist in the cross.

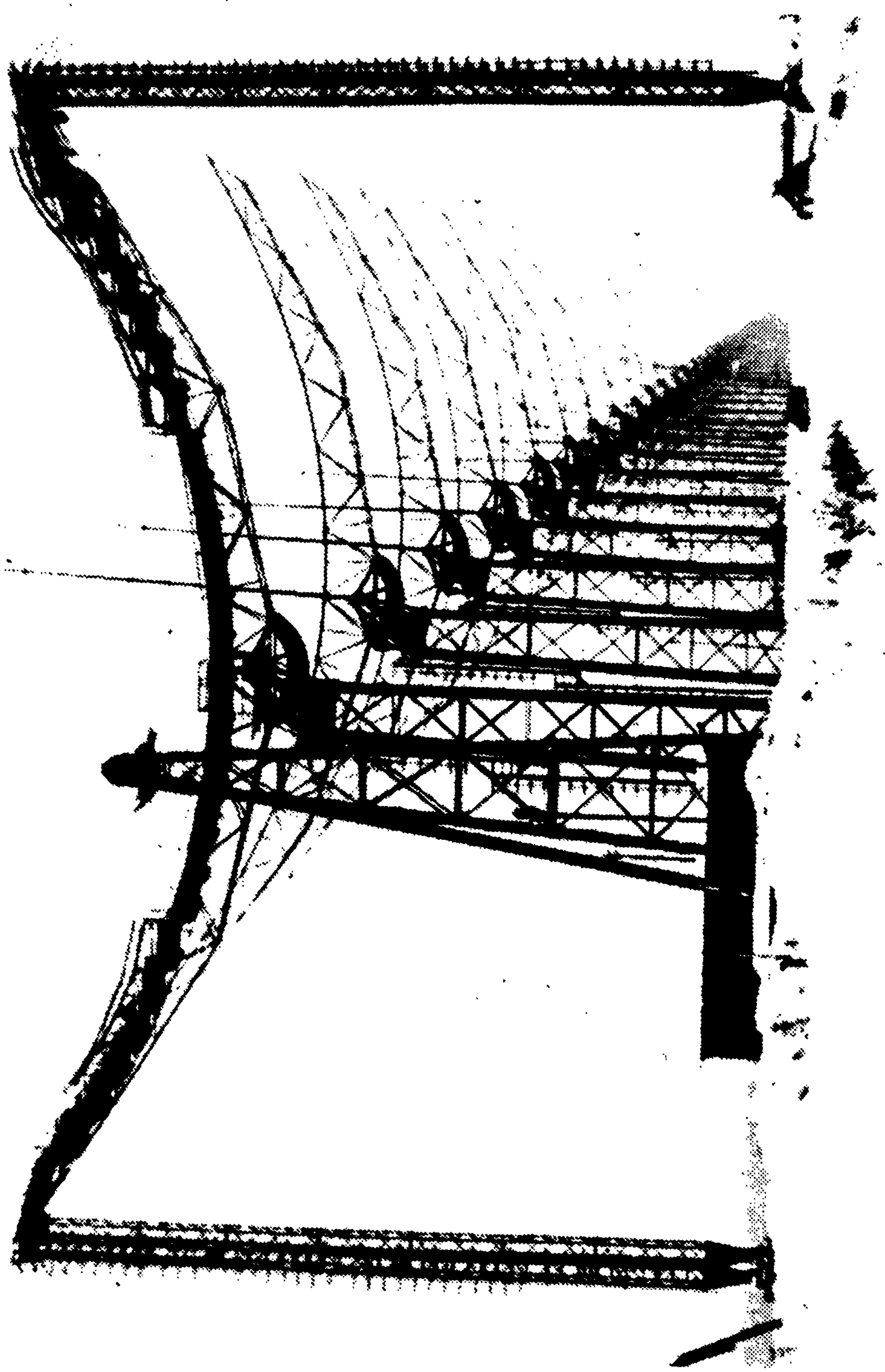


Figure 18 Serpukhov (Russia) 3, 280-foot Cross Antenna (E-W Arm)

3.2.5 University of Cambridge 3300-Foot Aperture Synthesis Telescope

All the interferometer techniques that we have discussed so far are performed in real time. If the radio astronomer is surveying a large area of sky wherein the brightness distribution remains unchanged over a long period of time, he can achieve the high resolution of switched interferometers, such as is obtained with the T design, but with less metal by an aperture-synthesis technique.

Intuitively, it can be appreciated that a large antenna can be synthesized by a pair of elements that cover successively the physical area that would be occupied by the large antenna. By sampling the incident energy with the elements at different positions and combining the separate observations in a computer where amplitude and phase weighting factors can be assigned to the different inputs, it is possible to synthesize any type of aperture and to direct its main beam toward various portions of the sky. The problem of antenna construction is then replaced by one of computation or signal processing.

The sketches in Figure 19 show how aperture synthesis has been used at the University of Cambridge to simulate a cross antenna and an interferometer (Ref. 46), each having the equivalent collecting area of about 200,000 square feet. The cross consists of a fixed-corner reflector, 3300 feet long and 40 feet wide, and a similar element, 100 feet long and 40 feet wide, which occupies successive locations along a 1700-foot track that forms a T. At 38 Mc/s the beamwidth is 47'.

The interferometer consists of a fixed cylindrical parabola, 1450 feet long and 65 feet wide, and a movable element, 190 feet long by 65 feet wide, which occupies successive positions along a 1000-foot track whose axis lies 2570 feet away from the phase center of the fixed element. Figure 20 is a view of the cylindrical parabola, and Figure 21 shows the movable element (Ref. 47). Both of these elements have been used in a radio-star survey to generate a synthesized beamwidth of 18' by 25' at 178 Mc/s for a cost of only $2 per square yard of equivalent aperture (Ref. 48).

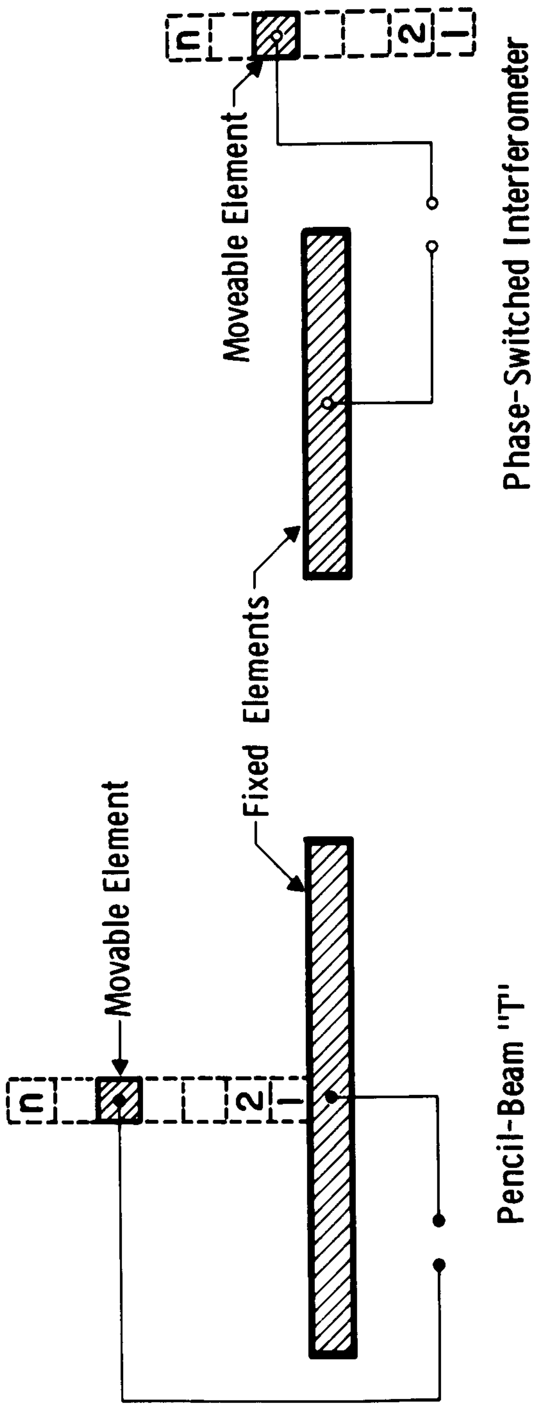


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Figure 19 Aperture Synthesis Techniques

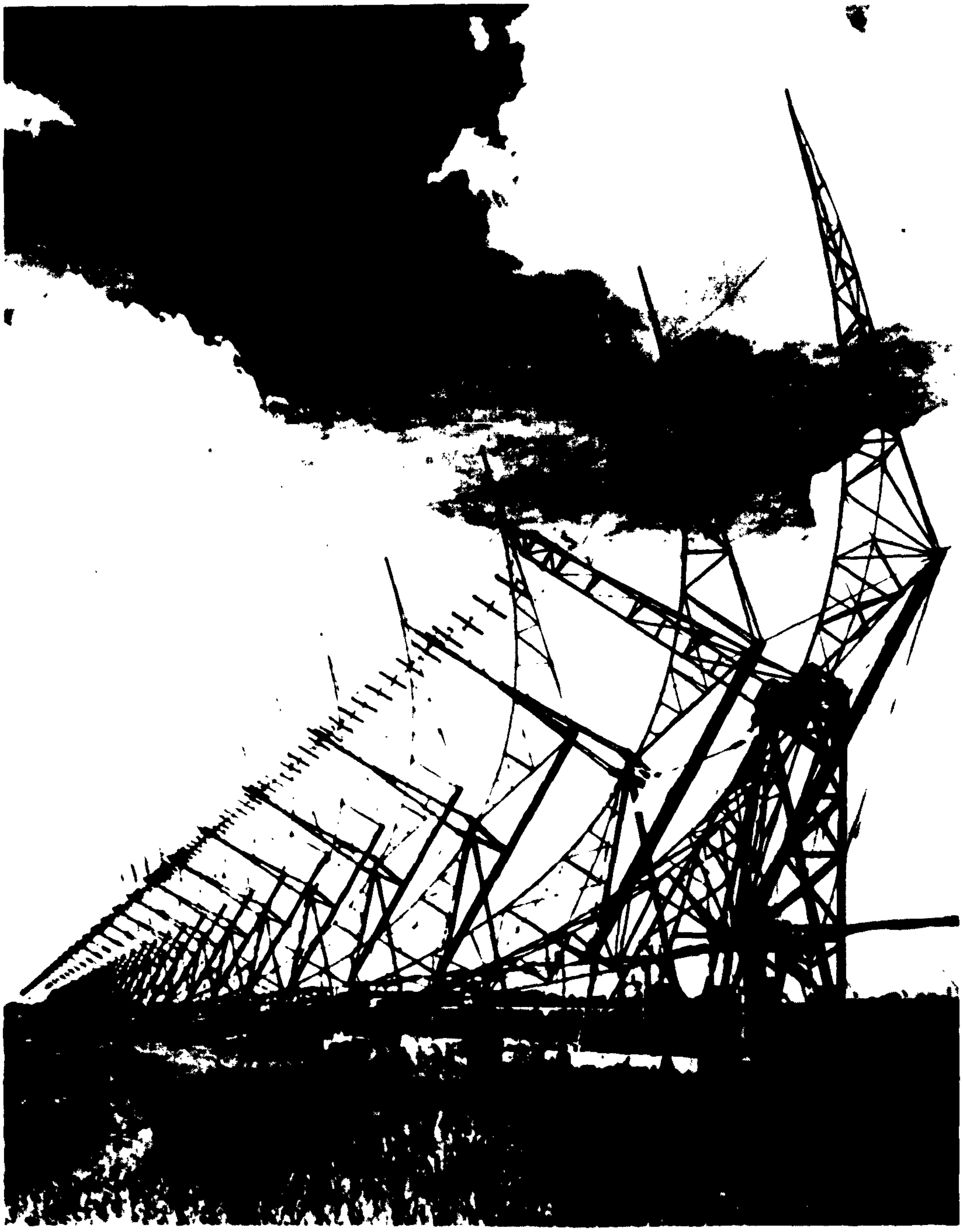

Figure 20 University of Cambridge (England) 1, 450-foot Aperture-Synthesis Telescope

Figure 21 Moveable Element of Aperture-Synthesis Interferometer

SECTION 4
FUTURE DEVELOPMENTS

4.1 SINGLE APERTURES

4.1.1 Reflectors

The near future probably will see more steerable parabolic and spherical reflectors in the 100- to 300-foot range. The development of fixed-reflector systems of comparable size and new feeds for beam adjustment is also anticipated.

In this regard, work done at the Naval Ordnance Test Station in China Lake, California, on Fresnel zone mirrors (Ref. 49) is worthy of mention. The zone plate, which consists of a series of concentric rings alternately transparent and opaque to electromagnetic radiation, produces a beamwidth equal to that of a paraboloid with the same diameter. However, the gain is about 15 db less because instead of focusing all incident energy into the feed, the zone plate scatters a great portion of it.

4.1.2 Lenses

More work on refractors (lenses) as competitors to small- and medium-sized reflectors needs to be done. The limited work performed by the University of Texas at millimeter wavelengths on a dielectric lens backed by a metallic reflector (Ref. 50), and the wire-grid lens antenna developed at the Stanford Research Institute (Ref. 51) are examples of what can be done.

4.1.3 Stepped-Zone Mirrors

Studies on stepped-zone mirrors for microwaves at the Centro Microonde in Italy (Ref. 52) represent an area that will be explored further. The purpose of the stepped-zone mirror is to collimate a beam from a large aperture over a wide scan angle without the spherical aberration found in spherical reflectors and without the coma developed in parabolas when the feed is moved off axis.

Figure 22 shows a cylindrical mirror with a quasi-parabolic mean cross-section, whose actual shape is a diffraction grating that focuses energy at a focus the locus of which follows the dashed curve shown for a $\pm 20^{\circ}$ scan angle and an f/D of unity. The bandwidth, however, is limited and is proportional to the focal length.

4.2 MULTIPLE APERTURES

While it is desirable to achieve a resolution of 1', assuming also a concomitant pointing accuracy of a few seconds, it would take years to survey the whole sky. Moreover, with such resolution one might like to observe short-lived phenomena on different parts of the sun's surface at the same time. It seems, therefore, economical to invest in the electronics required to feed a large, multi-purpose array which generates several beams simultaneously. Observing in several adjacent directions at once, and thus coming close to an image-forming telescope, is one of the goals of radio telescopists.

It is interesting to note that multiple 1' beams at 1420 Mc/s will be generated by the Benelux Cross Antenna in Holland, presently being designed with arms nearly 1 mile long (Refs. 54, 55). The antenna consists of one hundred paraboloids 100 feet in diameter arranged in two arrays forming a cross, as shown in Figure 23.

4.2.1 Multi-Beam Antennas

In a recent report to the National Science Foundation by its Advisory Panel on Radio Telescopes (Ref. 53), three approaches were highlighted for future radio telescopes designed to provide a 1-minute beam at 1420 Mc/s. One of these is a very large (2400-foot) fixed spherical reflector with closed-loop, servo-positioning for the feed; a second is a zoned reflector that consists of many plates spread over a large area, each focusing the intercepted signal to a common point; and the third is a long cross of large (200-foot) steerable paraboloids.

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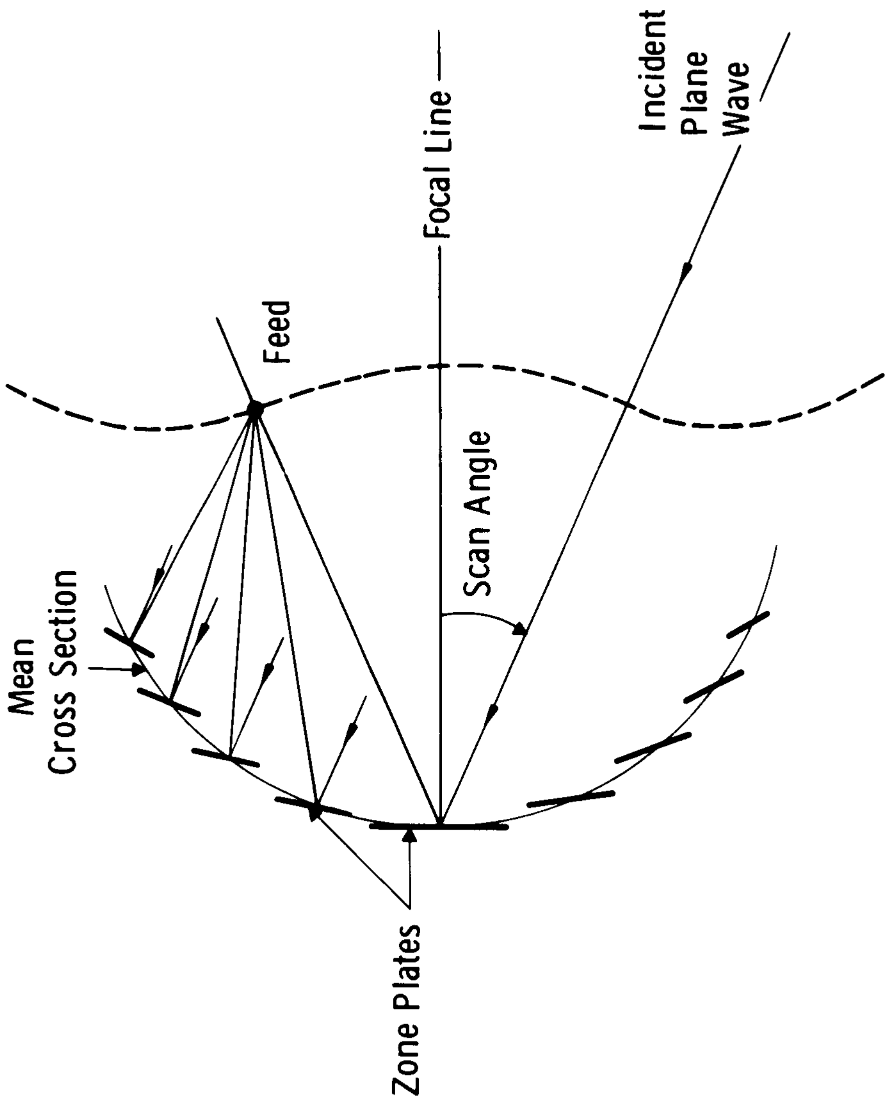


Figure 22 Stepped-Zone Cylindrical Mirror

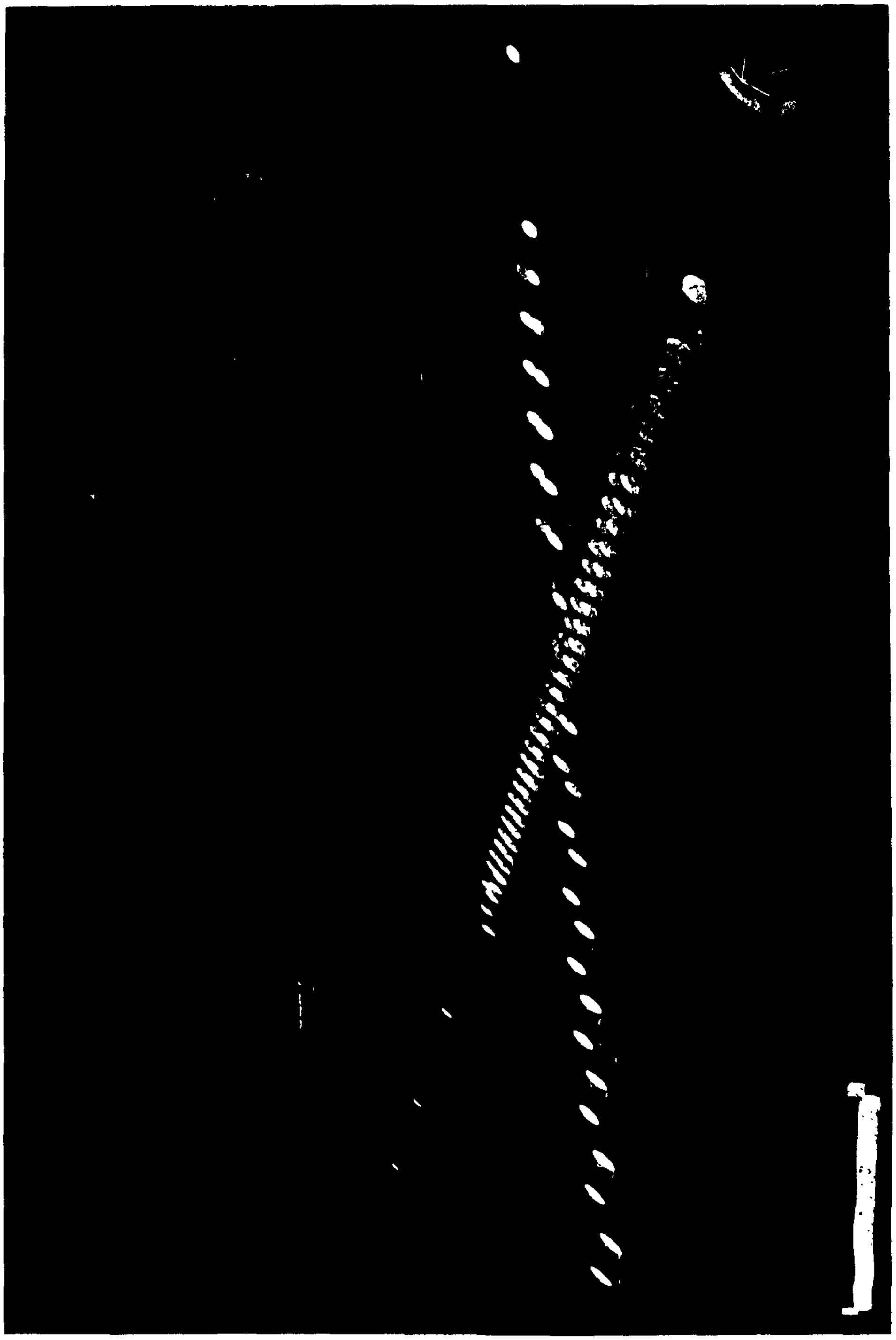


Figure 23 Benelux Cross Antenna

4.2.2 Venetian Blind Array

The grating responses of interferometric arrays are undesirable if one intends to detect without confusion a faint source amidst a field of stronger ones. The technique of switched interferometers has been adapted recently by Swarup (Ref. 56) of the Stanford University Radio Astronomy Institute to a large array of tiltable, parabolic cylinders built low to the ground, nicknamed the Venetian Blind Array and shown in Figures 24 and 25.

The array consists of any desired number of equally spaced elements, as shown in Figure 25. One of the two end elements is staggered about half a spacing with respect to the other equally spaced elements. The response pattern of the two end elements is multiplied with that of the main array to compensate for the gaps in the echelon formation (Ref. 57).

In the plane of the array, the power radiation pattern that results from phase-switching the two end elements with an 8-element linear array is shown in Figure 26. The normalized pattern of the whole system is given by

$$P = E(\theta) \cdot \frac{\sin 8x}{8 \sin x} \cdot \cos 9\text{-}1/2x \cdot \cos 1/2x,$$

where

$$x = \frac{\pi L}{\lambda} \sin \theta$$

L = separation between elements, except for one of the end elements whose spacing relative to its neighbor is 3L/2.

The first term, E(θ), is the power pattern of a single element; the second term is the pattern of the 8-element array; the third term results from the total number of 10 elements in the system; and the fourth term arises from a displacement of one-half spacing between the phase center of the array and that of the two end elements.

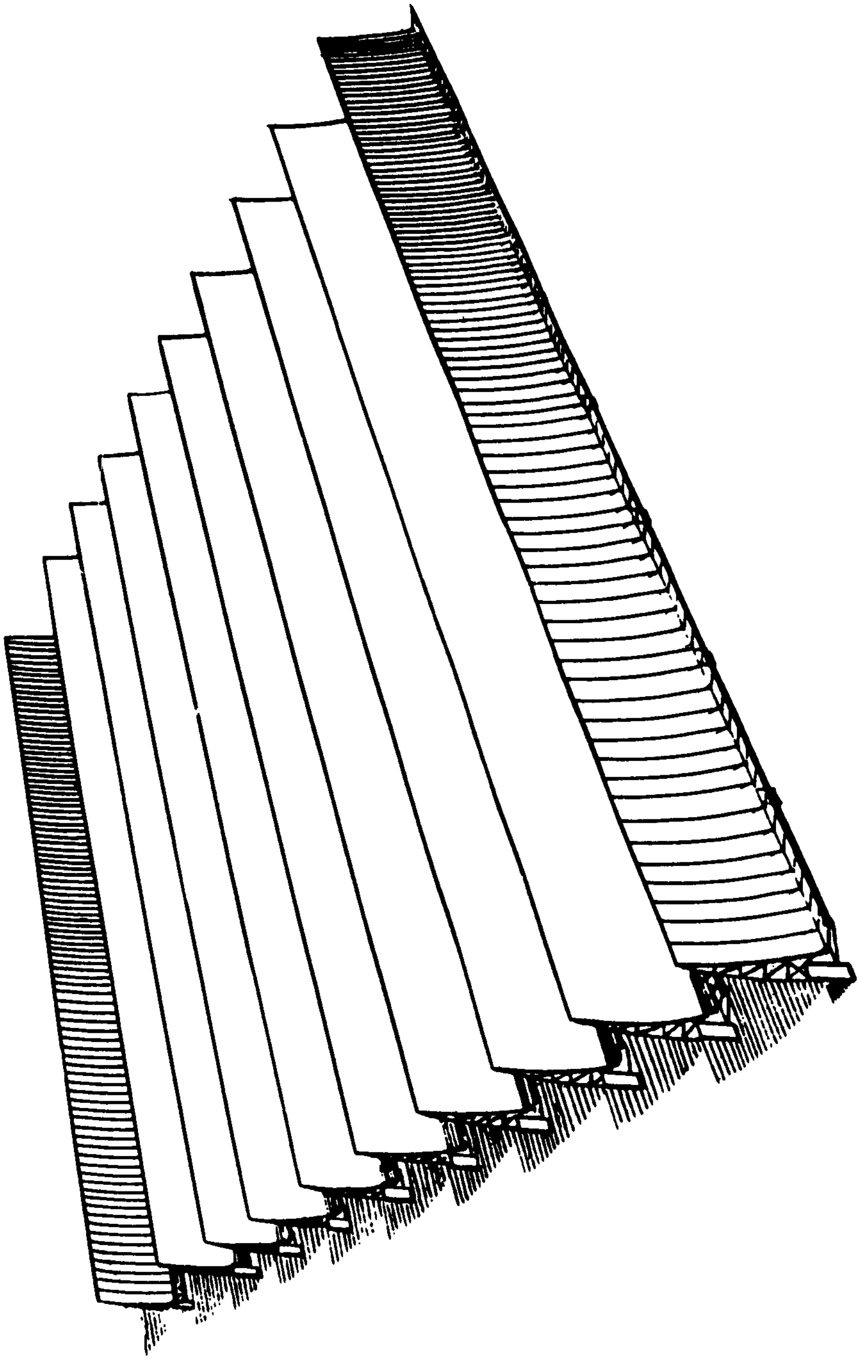
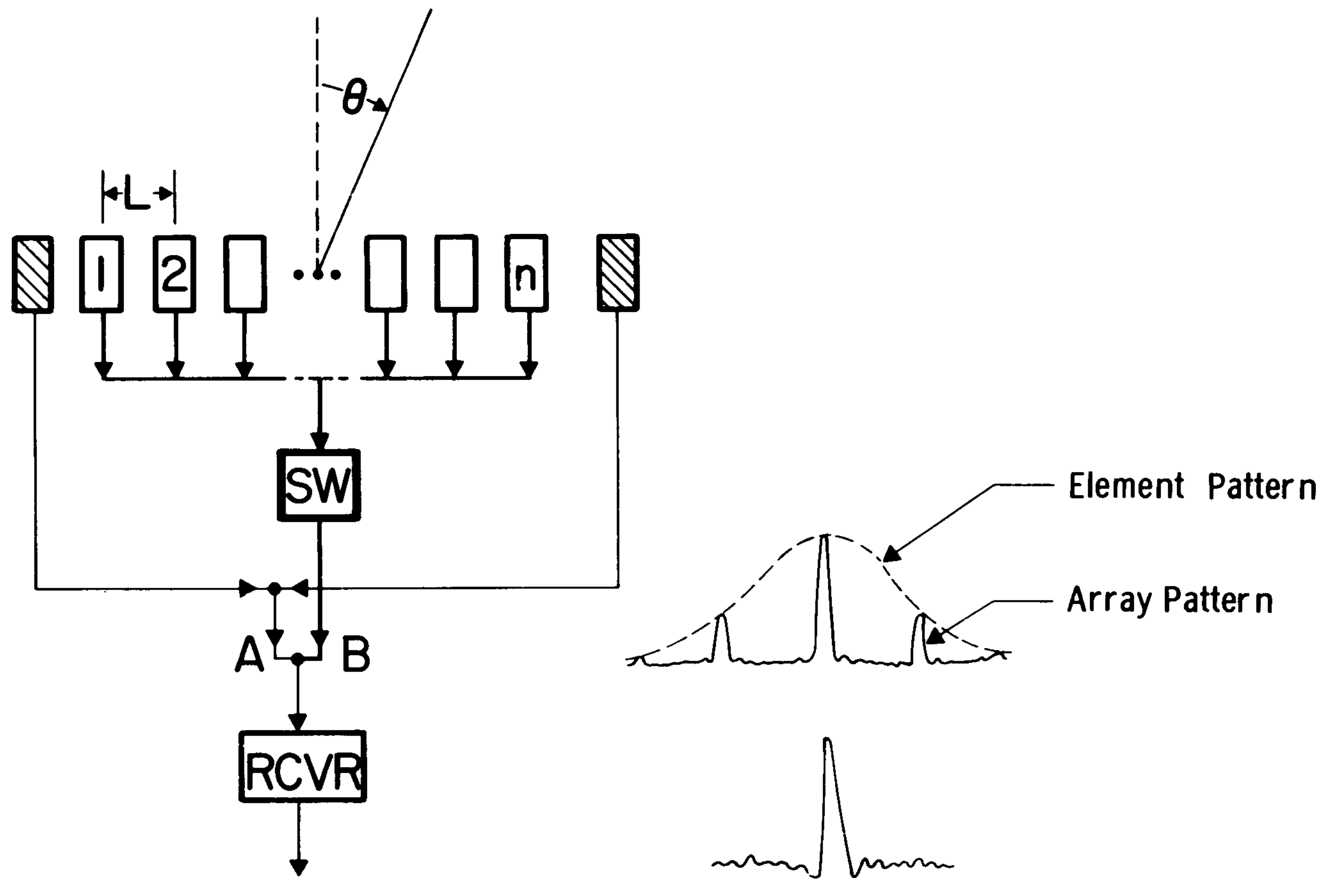


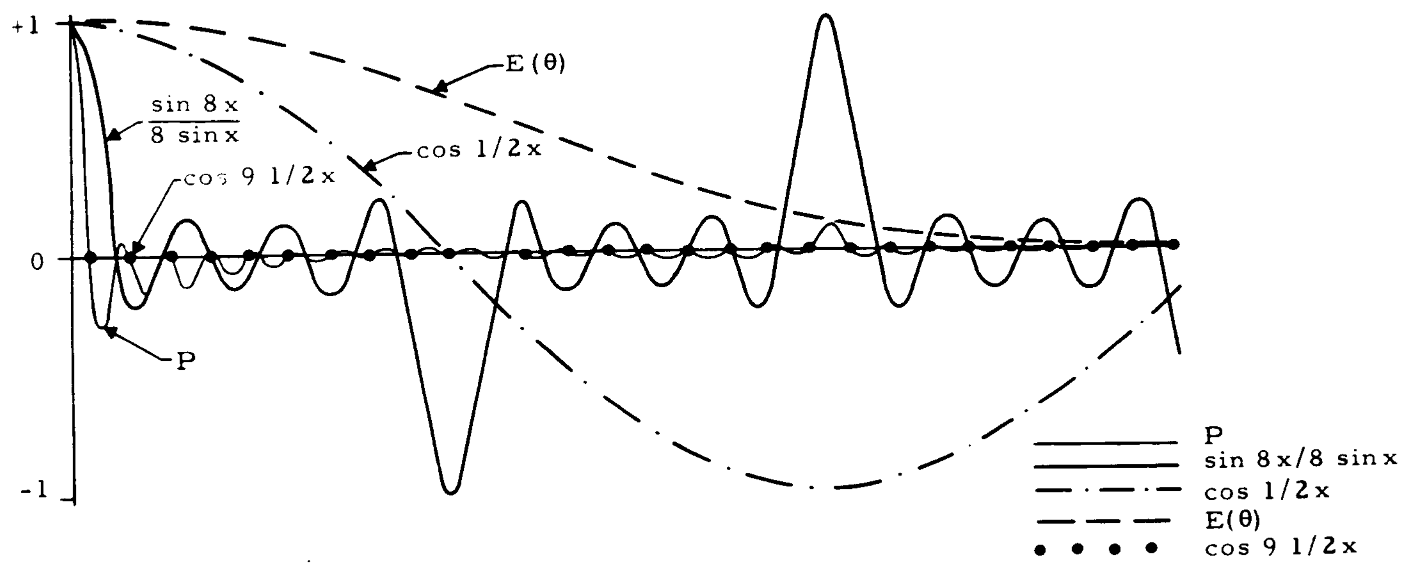
Figure 24 Pictorial View of Venetian Blind Array



$$P = A\,B = E(\theta)\cdot\frac{\sin 8x}{\sin x}\cdot \cos 9\tfrac{1}{2}x\cdot\cos\ x$$

A11242-P

Figure 25 Schematic, Venetian Blind Array Antenna



$$P = E(\theta) \cdot \frac{\sin 8x}{8 \sin x} \cdot \cos 9\,1/2x \cdot \cos 1/2x$$

10074-P

Figure 26 Normalized Power Radiation Pattern of Venetian Blind Array

The cost of such an array rises linearly with area rather than the cube of the diameter, as occurs with steerable paraboloids, and can be constructed progressively on a yearly basis. Consequently, its funding is predictable and its use is immediate as soon as one element is built. As time and construction progress, the use of the instrument multiplies. For example, any two elements can be used as a two-element interferometer; several equi-spaced elements can operate as a grating interferometer; and the end section of one of these elements can be detached and moved normal to the parent element to function as an aperture-synthesized T-cross. To increase resolution and sensitivity, more elements can be added, or the lengths of existing elements can be extended by adding sections, subject to the limitations of real estate. To scan the beam, the parabolic cylinders can be tilted about the long axis by synchronized motors, and the elements of an array feed (e. g., dipoles, horns, slotted waveguide) can be phased with linear phase gradients to move the beam in the orthogonal plane.

4.2.3 Other Arrays

The circular array has been explored analytically by Wild (Ref. 58) at the Australian National Radio Astronomy Observatory and compared to the Mills Cross. The Ford Foundation has recently awarded funds for the construction of a circular array with 100 42-foot steerable paraboloids to generate multiple 3.5' beams at 85 Mc/s (Ref. 59).

With the increased activity in solar radar astronomy and in the attempt to probe planetary atmospheres and the interplanetary medium, it is very likely that the future will also see more arrays such as the Lincoln Laboratory dipole array (Ref. 60) at El Campo, Texas, shown in Figure 27, and the Stanford University log-periodic array (Ref. 61) at Stanford, California, shown in Figure 28.

A catalogue of developments during the next five to ten years promises to be as fascinating as those of the last decade (Ref. 62).

Figure 27 Lincoln Laboratory 1, 700-foot Dipole Array

Figure 28 Stanford University Log-Periodic Array

SECTION 5
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